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VIDE: The Void IDentification and Examination toolkit☆

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ABSTRACT

We present VIDE, the Void IDentification and Examination toolkit, an open-source Python/C++ code for finding cosmic voids in galaxy redshift surveys and N-body simulations, characterizing their properties, and providing a platform for more detailed analysis. At its core, VIDE uses a substantially enhanced version of ZOBOV (Neyinck 2008) to calculate a Voronoi tessellation for estimating the density field and performing a watershed transform to construct voids. Additionally, VIDE provides significant functionality for both pre- and post-processing: for example, VIDE can work with volume- or magnitude-limited galaxy samples with arbitrary survey geometries, or dark matter particles or halo catalogs in a variety of common formats. It can also randomly subsample inputs and includes a Halo Occupation Distribution model for constructing mock galaxy populations. VIDE uses the watershed levels to place voids in a hierarchical tree, outputs a summary of void properties in plain ASCII, and provides a Python API to perform many analysis tasks, such as loading and manipulating void catalogs and particle members, filtering, plotting, computing clustering statistics, stacking, comparing catalogs, and fitting density profiles. While centered around ZOBOV, the toolkit is designed to be as modular as possible and accommodate other void finders. VIDE has been in development for several years and has already been used to produce a wealth of results, which we summarize in this work to highlight the capabilities of the toolkit. VIDE is publicly available at http://bitbucket.org/cosmicvoids/vide_public and http://www.cosmicvoids.net.

1. Introduction

Cosmic voids are emerging as a novel probe of both cosmology and astrophysics, as well as fascinating objects of study themselves. These large empty regions in the cosmic web, first discovered over thirty years ago (Gregory and Thompson, 1978; Jõeveer et al., 1978; Kirshner et al., 1981), are now known to fill up nearly the entire volume of the Universe (Hoyle and Vogeley, 2004; Pan et al., 2012; Sutter et al., 2012b). These voids exhibit some intriguing properties. For example, while apparently just simple vacant spaces, they actually contain a complex, multi-level hierarchical dark matter substructure (van de Weygaert and van Kampen, 1993; Gottlober et al., 2003; Aragon-Calvo and Szalay, 2013). Indeed, the interiors of voids appear as miniature cosmic webs, albeit at a different mean density (Goldberg and Vogeley, 2004). However, these void substructures obey simple scaling relations

☆ This code is registered at the ASCL with the code entry ASCL: 1407.014.

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that enable direct translations of void properties between different tracer types (e.g., galaxies and dark matter) (Benson et al., 2003; Ricciardelli et al., 2014; Sutter et al., 2013a). Their internal growth is relatively simple: voids do not experience major merger events over their long lifetimes (Sutter et al., 2014a) and their interiors are largely unaffected by larger-scale environments (Dubinski et al., 1993; Fillmore and Goldreich, 1984; van de Weygaert et al., 2010b).

As underdense regions, voids are the first objects in the large-scale structure to be dominated by dark energy. This fact coupled with their simple dynamics makes them a unique and potentially potent probe of cosmological parameters, either through their intrinsic properties (e.g., Biswas et al., 2010; Bos et al., 2012), exploitation of their statistical isotropy via the Alcock–Paczyński test (Lavaux and Wandelt, 2012; Sutter et al., 2012a, 2014c), or cross-correlation with the cosmic microwave background (Thompson and Vishniac, 1987; Granett et al., 2008; Ilić et al., 2013; Planck Collaboration, 2013; Cai et al., 2014). Additionally, fifth forces and modified gravity are unscreened in void environments, making them singular probes of exotic physics (e.g., Li et al., 2012; Clampitt et al., 2013; Spolyar et al., 2013; Carlesi et al., 2014).

Voids offer a unique laboratory for studying the relationship between galaxies and dark matter unaffected by complicated baryonic physics. As noted above, there appears to be a self-similar relationship between voids in dark matter distributions and voids in galaxies (Sutter et al., 2013a) via a universal density profile (Hamaus et al., 2014a, hereafter HSW). Void-galaxy cross-correlation analyses also reveal a striking feature: the large-scale clustering power of compensated voids is identically zero, which may give rise to a static cosmological ruler (Hamaus et al., 2014b). Observationally, measurements of the anti-lensing shear signal of background galaxies have revealed the internal dark matter substructure in voids (Melchior et al., 2014; Clampitt and Jain, 2014), and Ly-alpha absorption measurements have illuminated dark matter properties in void outskirts (Tejos et al., 2012). Finally, studying the formation of void galaxies reveals the secular evolution of dark matter halos (Rieder et al., 2013) and their mass function (Neyrinck et al., 2014).

Voids present a useful region for investigating astrophysical phenomena, as well. For example, the detection of magnetic fields within voids constrains the physics of the primordial Universe (Taylor et al., 2011; Beck et al., 2013). Contrasting galaxies in low- and high-density environments probes the relationship between dark matter halo mass and galaxy evolution (van de Weygaert and Platen, 2011; Kreckel et al., 2011; Ceccarelli et al., 2012; Hoyle et al., 2012).

Given the burgeoning interest in voids, there remains surprisingly little publicly-accessible void information. There are a few public catalogs of voids identified in galaxy redshift surveys, primarily the SDSS (e.g., Pan et al., 2012; Sutter et al., 2012b; Nadathur and Hotchkiss, 2014; Sutter et al., 2013c, 2014c), and there are fewer still catalogs of voids found in simulations and mock galaxy populations (Sutter et al., 2013a). And while there are many published methods for finding voids based on a variety of techniques, such as spherical underdensities (Hoyle and Vogeley, 2004; Padilla et al., 2005), watersheds (Platen et al., 2007; Neyrinck, 2008), and phase-space dynamics (Lavaux and Wandelt, 2010; van de Weygaert et al., 2010a; Sousbie, 2011; Cautun et al., 2013; Neyrinck et al., 2013), most codes remain private. In order to accommodate the expanding application of voids and to engender the development of communities and collaborations, it is essential to provide easy-to-use, flexible, and strongly supported void-finding codes.

In this paper we present VIDE,[1] for Void IDentification and Examination, a toolkit based on the publicly-available watershed code ZOBOV (Neyrinck, 2008) for finding voids but considerably enhanced and extended to handle a variety of simulations and observations. VIDE also provides an extensive interface for analyzing void catalogs. In Section 2 we outline the input data options for void finding, followed by Section 3 where we describe our void finding technique and our extensions and modifications to ZOBOV. Section 4 details our Python-based analysis toolkit functionality, and Section 5 is a quick-start user's guide. We summarize and provide an outlook for future uses and upgrades to VIDE in Section 6.

[1] The French word for "empty".

2. Input data options

2.1. Simulations

To identify voids in N-body dark matter populations, VIDE is able to read `Gadget` (Springel, 2005), `FLASH` (Dubey et al., 2008), and `RAMSES` (Teyssier, 2002) simulation outputs, files in the Self-Describing Format (Warren, 2013), and generic ASCII files listing positions and velocities. Void finding can be done on the dark matter particles themselves, or in randomly subsampled subsets with user-defined mean densities. Subsampling can be done either in a post-processing step or *in situ* during void finding.

VIDE can also find voids in halo populations. The user must provide an ASCII file and specify the columns containing the halo mass, position, and other properties. The user can use all identified halos or specify a minimum mass threshold for inclusion in the void finding process.

The user may construct a mock galaxy population from a halo catalog using a Halo Occupation Distribution (HOD) formalism (Berlind and Weinberg, 2002). HOD modeling assigns central and satellite galaxies to a dark matter halo of mass M according to a parametrized distribution. VIDE implements the five-parameter model of Zheng et al. (2007), where the mean number of central galaxies is given by

$$\langle N_{\rm cen}(M)\rangle = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right] \tag{1}$$

and the mean number of satellites is given by

$$\langle N_{\rm sat}(M)\rangle = \langle N_{\rm cen}(M)\rangle \left(\frac{M - M_0}{M_1'}\right)^{\alpha}, \tag{2}$$

where $M_{\rm min}$, $\sigma_{\log M}$, M_0, M_1', and α are free parameters that must be fitted to a given survey. The probability distribution of central galaxies is a nearest-integer distribution (i.e., all halos above a given mass threshold host a central galaxy), and satellites follow Poisson statistics. These satellites are placed around the central galaxy with random positions assuming a probability given by the NFW (Navarro et al., 1996) profile for a halo of the given mass. The user can also specify an overall mean density in case the HOD model was generated from a simulation with different cosmological parameters than the one used for void finding, which causes a mismatch in the target galaxy density. While not a full fix (which would require a new HOD fit), this at least alleviates some of the mismatch.

We have included – but not fully integrated into the pipeline – a separate code for fitting HOD parameters to a given simulation. The implemented model has three parameters, and given two of those the third is fixed by demanding that the abundance of galaxies of a given population reproduces the observed value. We then explore the 2-dimensional space of the other two parameters trying to minimize the χ^2 that results from comparing the two-point correlation function of the simulated galaxies with the observed data.